International Journal of Computing and Digital Systems
ISSN (2210-142X)
Int. J. Com. Dig. Sys. 9, No.2 (Mar-2020)
http://dx.doi.org/10.12785/ijcds/090210

Robust Adaptive Sliding Mode Control Design for Quadrotor Unmanned Aerial Vehicle Trajectory Tracking

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Received 13 Jul. 2019, Revised 22 Feb. 2020, Accepted 24 Feb. 2020, Published 01Mar. 2020

Abstract: The quadrotor unmanned aerial vehicles (UAV) systems have been getting more focus recently from researchers and engineers due to their outstanding impact and wide range of applications either in civilian or military. In this article, the sliding mode controller has been designed to control the attitude of the quadrotor as the inner loop controller. The major aim in this research is to reduce the chattering associated with the conventional sliding mode control (SMC), by implementing the adaptive fuzzy gain scheduling SMC technique (AFGS-SMC). Meanwhile, the performance of the proposed control has been evaluated in the presence of the model parameters uncertainty. The PD controller has been implemented as an outer loop controller to control the quadrotor position and supply the inner loop proposed controller (AFGS-SMC) with the desired generated quadrotor's attitude. Finally, the performance of the proposed AFGS-SMC controller has been evaluated by simulation in Matlab/Simulink platform, and compared with the classical SMC, in terms of chattering attenuation and robust trajectory tracking in the presence of the parameter uncertainty in the mass of the quadrotor UAV.

Keywords: Quadrotor UAV, PD Controller, SMC Control, Fuzzy Logic, Chattering, Gain Scheduling.

1. Introduction

In recent time, the quadrotor unmanned aerial vehicles (UAVs), gained a remarkable focus from researches and engineers due to its wide range of applications, in both military and civil sectors. The quadrotor UAVs consist of four independent controlled rotors which enable it to perform landing and take-off vertically. Quadrotors are considered as a promising platform for many applications such as surveillance, ecological monitoring, rescue operations, and aerial photography [1], [2]. As per the quadrotor's applications are significantly growing; consequently, a robust controller design is essential to enable the quadrotor to accomplish the assigned tasks.

The quadrotor is a nonlinear system, with an underactuated and coupled dynamics. These challenges must be considered in the controller design phase. There are many control techniques employed to the quadrotor, for instance, PID [3], [4], feedback linearization [5], [6], adaptive control [7], [8], and sliding mode controllers [9].

The sliding mode control (SMC) is a nonlinear controller that pushes the trajectories to reach the sliding surface in a finite time and stay on it thereafter. The main advantage of the SMC is the robustness against the parameter variations with a finite-time to reach the sliding surface [10]–[12]. However, the chattering problem is one of the main drawbacks of classical SMC.

There are several methods proposed in the literature to reduce the chattering influence by keeping the chattering within an acceptable limit [13]–[16]. The chattering leads to serious problems such as vibration in the mechanical parts and heating in electronics kits which increases the power consumption. Furthermore, the switching control in SMC control law induces high-frequency dynamics neglected in the modelling stage, such as unmodeled structural dynamic and time delay [17].

Fuzzy logic control (FLC) considered as one of the most brilliant applications of fuzzy set concept which introduced by Lutfi Zada at 1965 [18]. FLC is an essential branch of intelligent control filed that develops human experience and expertise about the plant in the controller design process. Moreover, it is a model-free method where the mathematical model is not required [19]. The AFGS-SMC controller has been designed for the attitude and the altitude in [2] while AFGS-SMC developed considering the attitude subsystem only [20], however in both works the outer loop controller for the position was not considered.

In this paper, AFGS-SMC controller has been developed as inner loop controller to stabilize and track the desired quadrotor attitude, while a fuzzy logic system (FLS) used to schedule sliding mode controller switching gain based on the deviation of state trajectories from

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sliding surface. The PD controller is used as an outer loop controller to stabilize the quadrotor's position and supply the inner loop proposed controller (AFGS-SMC) with the desired generated quadrotor's attitude. The performance of the proposed controller is examined under an ideal operating condition with nominal parameters, as well as in the presence of the quadrotor's mass uncertainty.

The rest of the article structured in the following pattern, section two briefly presented the quadrotor mathematical modelling. In section three, the proposed controllers (AFGS-SMC inner loop) is developed, and the PD is used as an outer loop control to generate the desired attitude. Section four showed the simulation results. Finally, section five concluded the article.

2. QUADROTOR DYNAMICS MODEL

A. *Model Description*

The quadrotor UAV composes from four rotors which fixed in a cross configuration as depicted in Figure 1 to generate the lift forces (F_1, F_2, F_3, F_4).

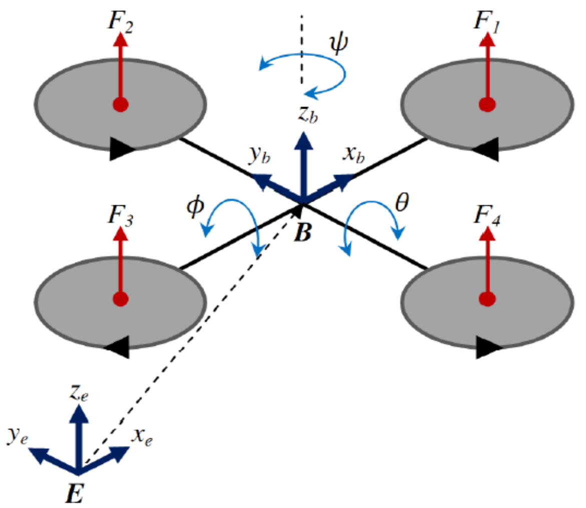

Figure 1. Quadrotor UAV configuration

The four rotors are divided into two pairs, rotors (1, 3) represent the front and rear, while rotors (2, 4) represent the left and the right rotors as depicted in Fig. 2. Rotors (1, 3) rotate in a clockwise direction, while rotors (2, 4) rotate in an anti-clockwise direction.

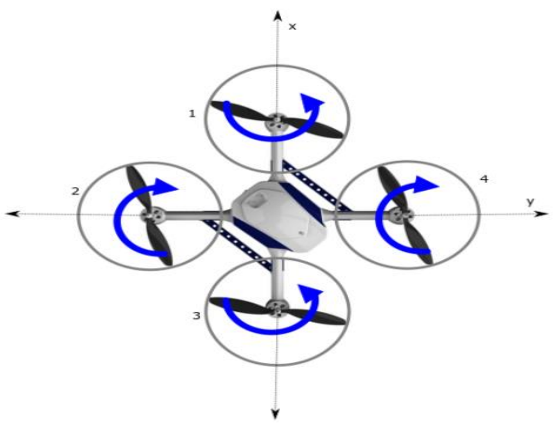

Figure 2. Rotors numbering in an anticlockwise direction

Table 1, and Figure. 3, are mapping all possible movements of the quadrotor in the free space.

TABLE 1 ALL POSSIBLE MOVEMENTS OF THE QUADROTOR ASSOCIATED WITH THE ROTORS' SPEEDS.

	Rotor(1)	Rotor(2)	Rotor(3)	Rotor(4)
Take-off	↑	↑	↑	↑
Landing	↓	↓	↓	↓
Right	-	↑	-	↓
Left	-	↓	-	↑
Forward	↓	-	↑	-
Backward	↑	-	↓	-
Clockwise	↓	↑	↓	↑
Anti-Clockwise	↑	↓	↑	↓

Where (↑) denotes the increment of the rotor speed, while (↓) denotes the decrement of the rotor speed. The increment and decrement of rotors speed happen simultaneously with the same proportion.

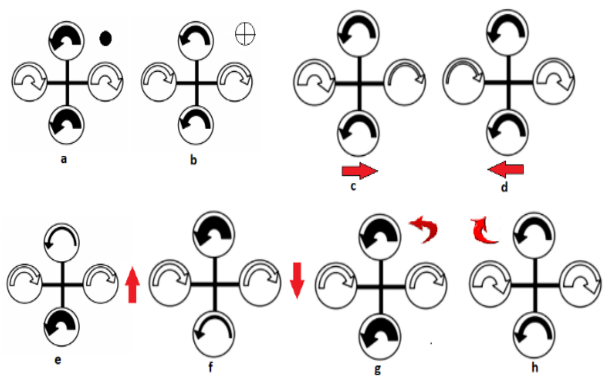

Figure 3. Quadrotor UAV Possible Motions

B. *Quadrotor UAV Kinematic Model*

There are two frames: earth fixed frame (E-frame) denoted by $\mathbf{E} = (x_e, y_e, z_e)$ and body fixed (B-frame) $\boldsymbol{B} = (x_b, y_b, z_b)$ as depicted in Figure 1.

Assume that $\boldsymbol{q} = (x, y, z, \phi, \theta, \psi) \in R^6$ represents the generalized coordinates of the quadrotor, where (x, y, z) are the quadrotor position, while (ϕ, θ, ψ) are the three Euler angles (literally are roll, pitch and yaw). The quadrotor mathematical model can be represented into two coordinate subsystems: the translational and the rotational subsystems. Therefore, the generalized coordinates of the quadrotor can be re-written as follows:

$$\boldsymbol{q} = [\boldsymbol{\xi}, \boldsymbol{\eta}]^T \tag{1}$$

Where,

$$\boldsymbol{\xi} = [x, y, z]^T \tag{2}$$

And,

$$\boldsymbol{\eta} = [\phi, \theta, \psi]^T \tag{3}$$

Where, $\boldsymbol{\xi}$ descripts the translational motion while $\boldsymbol{\eta}$ represents the rotational motion.

C. Quadrotor Dynamic Model

The dynamic equations of the quadrotor UAV are given as follows:

$$\begin{aligned}
\ddot{x} &= \frac{\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi}{m} u_4 \\
\ddot{y} &= \frac{\cos\phi \sin\theta \cos\psi - \sin\phi \sin\psi}{m} u_4 \\
\ddot{z} &= -g + \frac{\cos\phi \cos\theta}{m} u_4 \\
\ddot{\phi} &= \dot{\theta}\dot{\psi}\frac{I_y - I_z}{I_x} + \dot{\theta}\Omega_d \frac{J_r}{I_x} + \frac{1}{I_x} u_1 \\
\ddot{\theta} &= \dot{\phi}\dot{\psi}\frac{I_z - I_x}{I_y} + \dot{\phi}\Omega_d \frac{J_r}{I_y} + \frac{1}{I_y} u_2 \\
\ddot{\psi} &= \dot{\theta}\dot{\psi}\frac{I_x - I_y}{I_z} + \frac{1}{I_z} u_3
\end{aligned} \tag{4}$$

Where u_1, u_2, u_3, u_4 are the control inputs of the quadrotor UAV and have the following formula:

$$\begin{aligned}
u_1 &= b(\Omega_4^2 - \Omega_2^2) \\
u_2 &= b(\Omega_3^2 - \Omega_1^2) \\
u_3 &= d(\Omega_4^2 + \Omega_2^2 - \Omega_3^2 - \Omega_1^2) \\
u_4 &= b(\Omega_1^2 + \Omega_2^2 + \Omega_3^2 + \Omega_4^2)
\end{aligned} \tag{5}$$

While Ω_d represents the disturbance, and expressed as follows:

$$\Omega_d = -\Omega_1 + \Omega_2 - \Omega_3 + \Omega_4 \tag{6}$$

The control inputs (5) can be written in matrix as:

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = \begin{bmatrix} b & b & b & b \\ 0 & -b & 0 & b \\ -b & 0 & b & 0 \\ -d & d & -d & d \end{bmatrix} \begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix} \tag{7}$$

$$\begin{bmatrix} \Omega_1^2 \\ \Omega_2^2 \\ \Omega_3^2 \\ \Omega_4^2 \end{bmatrix} \begin{bmatrix} 0.25 & 0 & -0.5 & -0.25 \\ 0.25 & -0.5 & 0 & 0.25 \\ 0.25 & 0 & 0.5 & -0.25 \\ 0.25 & 0.5 & 0 & 0.25 \end{bmatrix} \begin{bmatrix} \frac{u_1}{b} \\ \frac{u_2}{b} \\ \frac{u_3}{b} \\ \frac{u_4}{b} \end{bmatrix} \tag{8}$$

3. CONTROL DESIGN

As depicted in Figure 4, the AFGS-SMC has been designed as an inner loop controller for quadrotor's attitude control, and PD has been designed as an outer loop controller for quadrotor's position control.

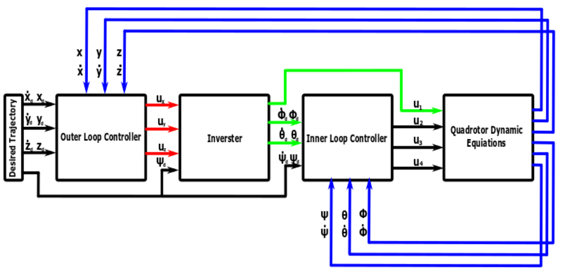

Figure 4. Overall quadrotor control system block diagram

A. Inner loop AFGS-SMC control

The control objective is to design the inner loop SMC controller to stabilize the attitude error dynamics. The desired attitude given by (ϕ_d,θ_d,ψ_d), while the measured attitude is (ϕ, θ, ψ) The SMC control task is to stabilize the error dynamics asymptotically, which yields to:

$$\begin{aligned}
\lim_{t\to\infty} e_\phi &= 0 \\
\lim_{t\to\infty} e_\theta &= 0 \\
\lim_{t\to\infty} e_\psi &= 0
\end{aligned} \tag{9}$$

where,

$$\begin{aligned}
e_\phi &= \phi - \phi_d \\
e_\theta &= \theta - \theta_d \\
e_\psi &= \psi - \psi_d
\end{aligned} \tag{10}$$

The first step is to define the tracking errors as in (10).

The second step is to select the sliding surface as follows, [1]:

$$s = \left(\frac{d}{dt} + k_x\right)^{n-1} e \tag{11}$$

Therefore, from (10) and (11) the sliding surfaces for attitude angles yields to,

$$\begin{aligned}
s_\phi &= \dot{e}_\phi + k_\phi e_\phi \\
s_\theta &= \dot{e}_\theta + k_\theta e_\theta \\
s_\psi &= \dot{e}_\psi + k_\psi e_\psi
\end{aligned} \tag{12}$$

where, s_ϕ,s_θ and s_ψ represent the sliding surfaces for roll, pitch and yaw, respectively. While k_ϕ,k_θ and k_ψ are positive constants (controller gains).

The 3rd step is to apply the sliding mode condition as follows,

$$\dot{s} = -k_1\, sgn(s) - k_2 s \tag{13}$$

Now, from equations (10), (12) and (13), yields to,

$$\begin{aligned}
\ddot{\phi} &= \ddot{\phi}_d - k_\phi \dot{e}_\phi - k_{1_\phi}\, sgn(s_\phi) - k_{2_\phi} s_\phi \\
\ddot{\theta} &= \ddot{\theta}_d - k_\theta \dot{e}_\theta - k_{1_\theta}\, sgn(s_\theta) - k_{2_\theta} s_\theta \\
\ddot{\psi} &= \ddot{\psi}_d - k_\psi \dot{e}_\psi - k_{1_\psi}\, sgn(s_\psi) - k_{2_\psi} s_\psi
\end{aligned} \tag{14}$$

where k_{1_ϕ},k_{1_θ},k_{1_ψ}>0 and k_{2_ϕ},k_{2_θ},k_{2_ψ}>0 are controller gains. Substitute (4) (the attitude subsystem) into (14) yields to the inner loop SMC control laws:

$$\begin{aligned}
u_2 &= I_x(\ddot{\phi}_d - a_1\dot{\theta}\dot{\psi} - a_2\dot{\theta}\Omega_d - k_\phi \dot{e}_\phi \\
&\quad - k_{1_\phi}\, sgn(s_\phi) - k_{2_\phi} s_\phi) \\
u_3 &= I_y(\ddot{\theta}_d - a_3\dot{\phi}\dot{\psi} - a_4\dot{\phi}\Omega_d - k_\theta \dot{e}_\theta \\
&\quad - k_{1_\theta}\, sgn(s_\theta) - k_{2_\theta} s_\theta) \\
u_4 &= I_z(\ddot{\psi}_d - a_5\dot{\phi}\dot{\theta} - k_\psi \dot{e}_\psi - k_{1_\psi}\, sgn(s_\psi) \\
&\quad - k_{2_\psi} s_\psi)
\end{aligned} \tag{15}$$

B. Chattering attenuation

The chattering is the phenomenon of finite-frequency, finite-amplitude oscillations occurred in control systems with sliding mode control [2]. Due to the presence of sign function in the designed SMC chattering will be induced in the controller output and the intensity of this chattering is proportional to the sign function gain. A FLS based on Takagi-Sugeno model is designed to change controller gains k_{1_ϕ},k_{1_θ},k_{1_ψ} (adaptively). Figure 5 depicts FLS general architecture where for roll, pitch and yaw angles

FLS input is sliding surface and its derivative while controller gains $(k_{1_\phi}, k_{1_\theta}, k_{1_\psi})$ is its output.

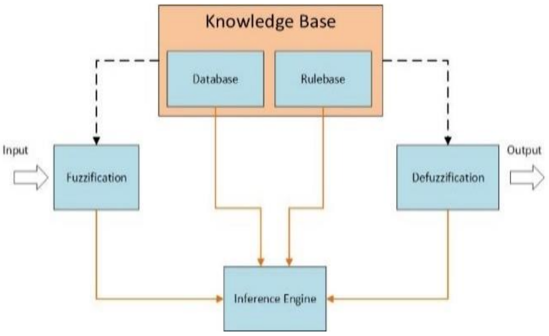

Figure 5. FLS general architecture

Unified Gaussian membership function is selected to represent the FLS inputs, while the output is represented by a constant membership function. Inputs sets are defined {NL, NS, ZE, PS, PL}, where "PL" indicates positive large, "PS" indicates positive small, "ZE" indicates zero, "NS" indicates negative small, and "NL" indicates negative large. While output sets selected as {VL, L, M, H, VH}, where "VH" indicates very high, "H" indicates high, "M" indicates medium, "L" indicates low, and "VL" indicates very low. Figure 6 shows the inputs membership function, and Figure 7 presents the FLS surface.

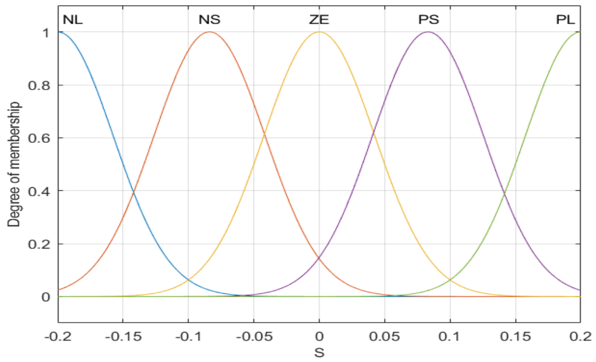

Figure 6. FLS inputs membership

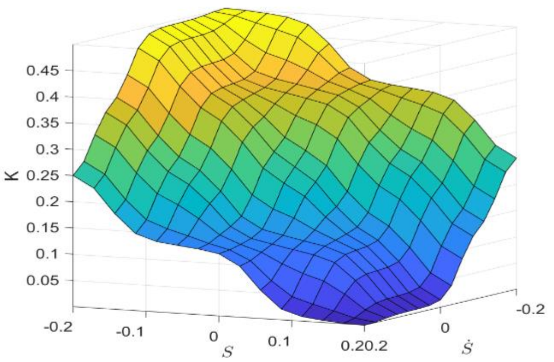

Figure 7. FLS surface

The rules are designed according to the deviation of state trajectories from the sliding surface, where the controller gain is high when state trajectories are far away from the sliding surface and low once the state trajectories reached sliding surface. Table 2 illustrates fuzzy rules.

TABLE 2. FUZZY RULES

k		$\dot{S}$				
		NL	NS	ZE	PS	PL
S	PL	M	L	VL	VL	VL
	PS	H	M	L	L	VL
	ZE	H	H	M	L	L
	NS	VH	H	H	M	L
	NL	VH	VH	VH	H	M

where each rule has the following form: If S is x and $\dot{S}$ is y, then output level k=c, (c *is a constant*). The FLS final output is given by the weighted average of the whole rules output[3].

$$output = \frac{\sum_{i=1}^{N} w_i k_i}{\sum_{i=1}^{N} w_i} \tag{16}$$

where w_i represents rule firing strength and N is the rules number.

C. Outer loop controller

The dynamic model of the quadrotor UAV presented in (4) is an underactuated system because there are six outputs $[x,y,z,\phi,\theta,\psi]^T$ which are controlled by four control inputs $[u_1,u_2,u_3,u_4]^T$ only. Therefore, to deal with this underactuated property, the virtual PD control inputs are designed as in [4], [5]. Therefore, the underactuated subsystem is:

$$\begin{aligned}\ddot{x} &= (\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi)\frac{u_1}{m}\\ \ddot{y} &= (\cos\phi\sin\theta\cos\psi - \sin\phi\sin\psi)\frac{u_1}{m}\\ \ddot{z} &= -g + (\cos\phi\cos\theta)\frac{u_1}{m}\end{aligned} \tag{17}$$

The above equation (17) can be written in the following format:

$$U = \begin{bmatrix}U_x\\U_y\\U_z\end{bmatrix} = \begin{bmatrix}\cos\phi\sin\theta\cos\psi + \sin\phi\sin\psi\\ \cos\phi\sin\theta\cos\psi - \sin\phi\sin\psi\\ \cos\phi\cos\theta\end{bmatrix}\frac{u_1}{m} - \begin{bmatrix}0\\0\\g\end{bmatrix} \tag{18}$$

where, $U = [\ddot{x}, \ddot{y}, \ddot{z}]^T$.

The virtual controls enable us to control the translation motion (position) along x, y, and z indirectly by the three inputs $(u_1, \phi_d$ and $\theta_d)$. As shown in Figure 8, the outer loop controller takes the desired (x_d, y_d, z_d) and actual (x, y, z) trajectory and generates the virtual controls (U_x, U_y, U_z). The invertor takes these virtual controls along with the desired yaw angel (ψ_d) as the inputs to generate the lift force (u_1), desired rolling (ϕ_d), and desired pitching (θ_d) motions.

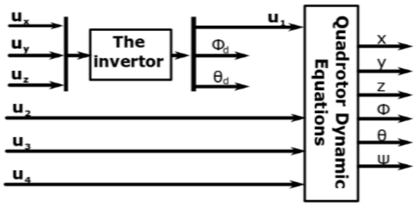

Figure 8. Virtual control inputs and outputs [4].

From (18), underactuated subsystem for the translation motions can be written as follows:

$$U_x = \frac{u_1}{m}(\cos\phi \sin\theta \cos\psi + \sin\phi \sin\psi)$$
$$U_y = \frac{u_1}{m}(\cos\phi \sin\theta \cos\psi - \sin\phi \sin\psi) \quad (19)$$
$$U_z = \frac{u_1}{m}(\cos\phi \cos\theta) - g$$

And, the error dynamic equations are,

$$e_x = x - x_d$$
$$e_y = y - y_d \quad (20)$$
$$e_z = z - z_d$$

The PD controller is implemented to generate the virtual control inputs as follows:

$$U_x = k_{I_x} e_x + k_{D_x} \dot{e}_x$$
$$U_y = k_{I_y} e_y + k_{D_y} \dot{e}_y \quad (21)$$
$$U_z = k_{I_z} e_z + k_{D_z} \dot{e}_z$$

where, $k_{I_x}, k_{I_y}, k_{I_z} > 0$ and $k_{D_x}, k_{D_y}, k_{D_z} > 0$. By taking the square of the both sides of (19), yields to the following the lift force,

$$u_1 = \sqrt{U_x^2 + U_y^2 + (U_z + g)^2} \quad (22)$$

The desired roll and pitch angles are,

$$\phi_d = \sin^{-1}\left(\frac{U_x \sin\psi_d - U_y \cos\psi_d}{u_1}\right) \quad (23)$$

$$\theta_d = \tan^{-1}\left(\frac{U_x \sin\psi_d + U_y \cos\psi_d}{U_z + g}\right) \quad (24)$$

4. SIMULATION MODEL

The Quadrotor mathematical model (4) is simulated using Matlab/Simulink platform, and the model parameters used in this simulation is taken from [6], as listed in Table 3. The numerical solution of the model along with the proposed controllers, is solved using the ode45 variable-step solver (the default). Table 3 and Table 4 are listed the AFGS-SMC and PD controllers gains, respectively.

TABLE 3. PARAMETERS OF THE QUADROTOR.

Name	Parameter	Value	Unit
mass	m	0.650	kg
inertia on x axis	I_x	7.5e-3	kgm^2
inertia on y axis	I_y	7.5e-3	kgm^2
inertia on z axis	I_z	1.3e-2	kgm^2
thrust coefficient	b	3.13e-5	Ns^2
drag coefficient	d	7.5e-7	Nms^2
rotor inertia	J_r	6e-5	kgm^2
arm length	l	0.23	m

TABLE 4. SMC CONTROLLER GAINS FOR THE INNER LOOP

Parameter	ϕ	θ	ψ
k	2	2	2
k_1	0.5	0.5	0.5
k_2	2	2	2

TABLE 5. PD CONTROLLER GAINS FOR THE OUTER LOOP

Parameter	x	y	z
k_I	2	2	2
k_D	1	1	1

5. SIMULATION RESULTS AND DISCUSSION

Two scenarios have been considered to assess the performance of the proposed controller. The first scenario shows the system response under ideal conditions using the nominal values of the system's parameters while the second scenario evaluates response at the presence of uncertainty. In both scenarios, the results compared to the classical SMC controller.

A) Scenario 1: Controlled system under ideal conditions:

Figure 9, Figure 10 and Figure 11 show position and attitude trajectory tracking, respectively. According to attitude errors shown in Figure 14, it can be observed that the classical SMC provides a slightly better tracking compare to the AFGS-SMC controller. However, the proposed AFGS-SMC controller outperforms the classical SMC in terms of the chattering reduction as depicted in Figure 12 and Figure 13, respectively which is play a critical role. Figure 15 depicts the adaptive gains where they are changing their amplitude according to the deviation of trajectories form sliding surface.

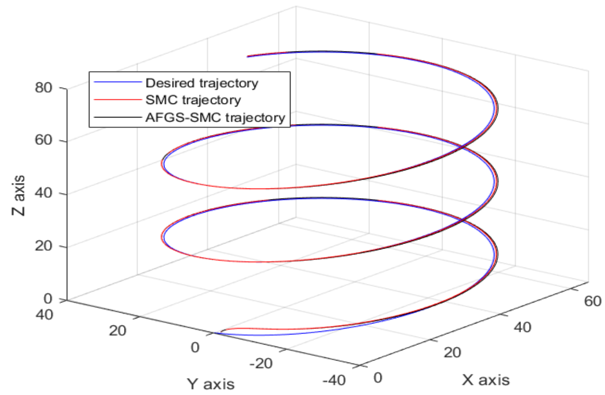

Figure 9. 3D Spiral trajectory tracking without uncertainty

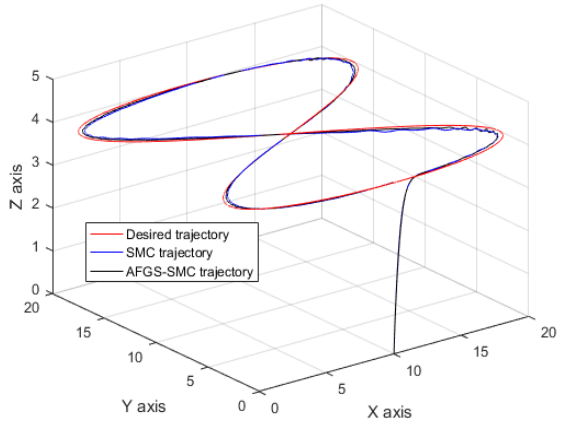

Figure 10. 3D 8-Shape trajectory tracking without uncertainty

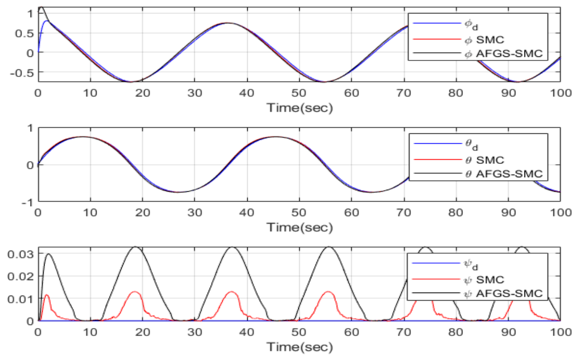

Figure 11. The attitude of the quadrotor

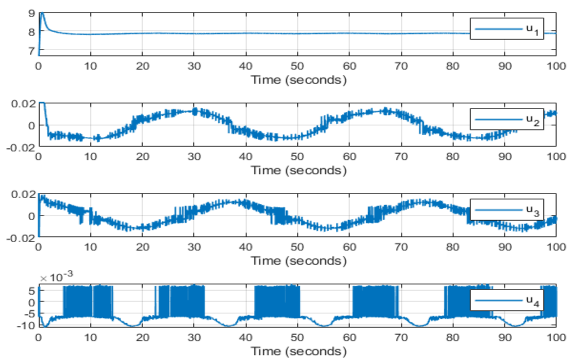

Figure 12. SMC Control efforts

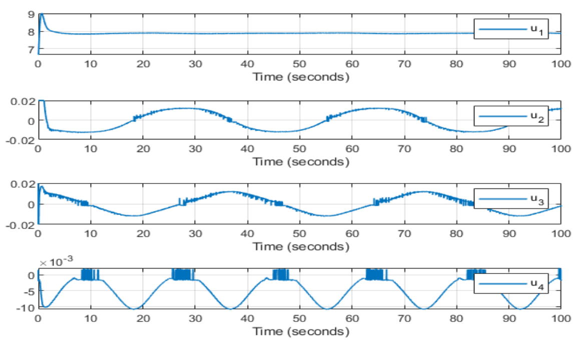

Figure 13. AFGS-SMC Control efforts

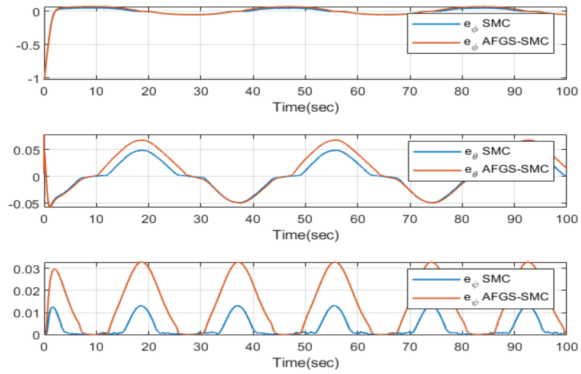

Figure 14. The attitude errors

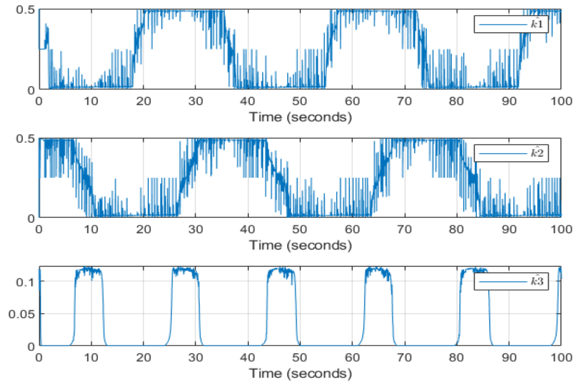

Figure 15. Control gains for AFGS-SMC

B) *Scenario 2: Controlled system under uncertainty*

The real-world quadrotor applications are not without parameters uncertainty, and in this scenario, we assume that the uncertainty happened in the mass of the quadrotor. This assumption can be interpreted by some existed applications of quadrotor such as payload-carrying, spraying agricultural pesticides, photography, etc. In all the above-mentioned applications, the mass of the quadrotor is affected in a direct way by attaching an extra/add weight (called added mass) which is called mass uncertainty in the field of control design, and the designed or proposed controller must be able to adapt this uncertainty (change in the mass).

Now, in this scenario, uncertainty has been introduced into the system mass (m), which has a powerful impact on system performance, as shown in Figure 16. At the time of 20 sec the mass has been increased by about 30% from the nominal value, while at time of 40 sec it has been backed to the nominal value, and again at the time of 60 sec the mass of the system has been changed by about 15% increment above the nominal value of the mass. Finally, at the time of 80 sec and onwards, the mass stayed at its nominal value.

Figure 17, Figure 18 and Figure 19 show the position and attitude trajectory tracking, respectively, at the presence of mass uncertainty. According to attitude errors shown in Figure 22, it can be observed that the classical SMC offers slightly better tracking than the AFGS-SMC controller. On the other hand, the proposed AFGS-SMC controller outperforms the classical SMC in terms of the chattering attenuation as exhibited in Figure 20 and Figure 21, respectively. Figure 23 depicts adaptive the gains where they are changing their amplitude according to the deviation of trajectories form sliding manifold.

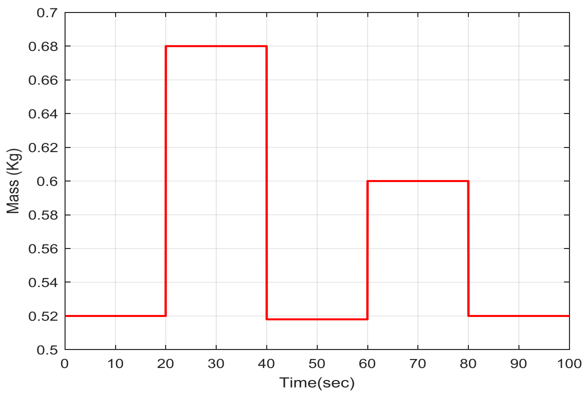

Figure 16. Mass uncertainty

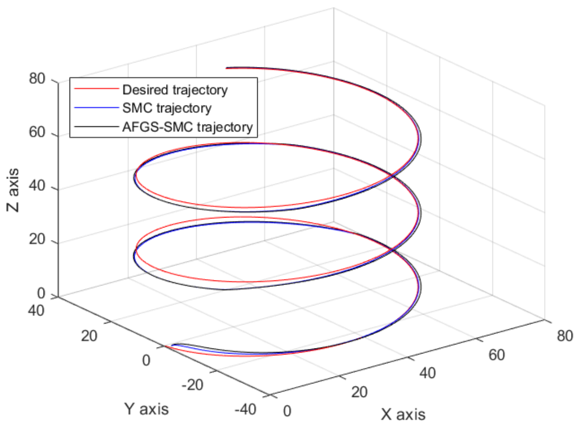

Figure 17. Trajectories tracking in 3D spiral shape under parameters uncertainty

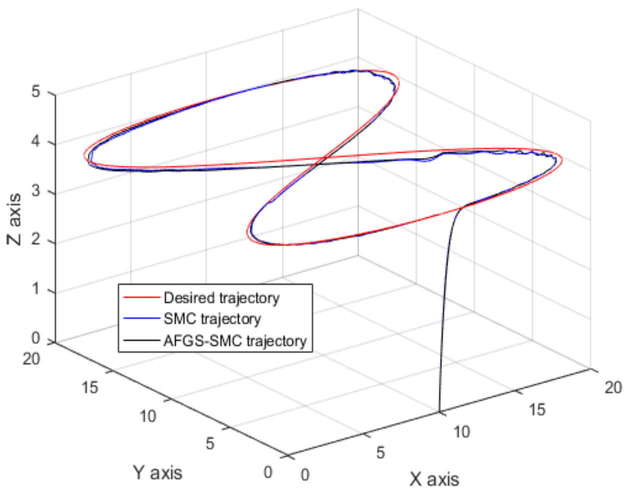

Figure 18. Trajectories tracking in 3D 8-shape under parameters uncertainty

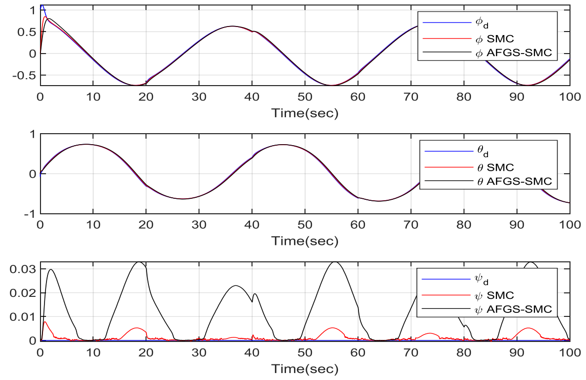

Figure 19. The attitude of the quadrotor under parameters uncertainty

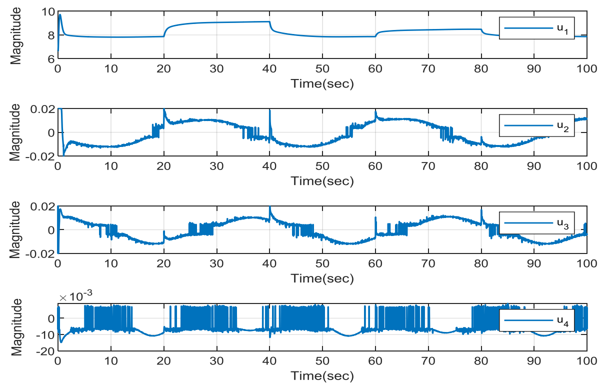

Figure 20. SMC Control efforts under parameters uncertainty

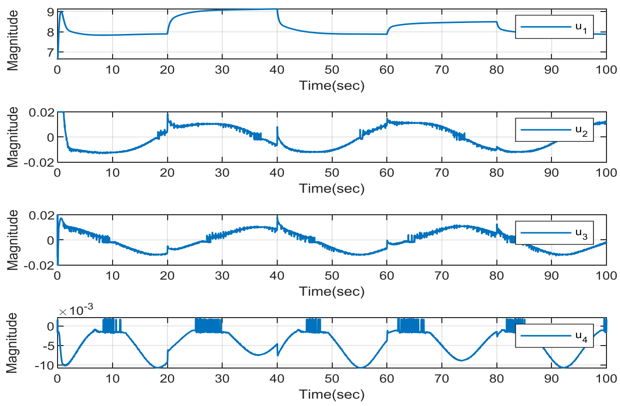

Figure 21. AFGS-SMC Control efforts under parameters uncertainty

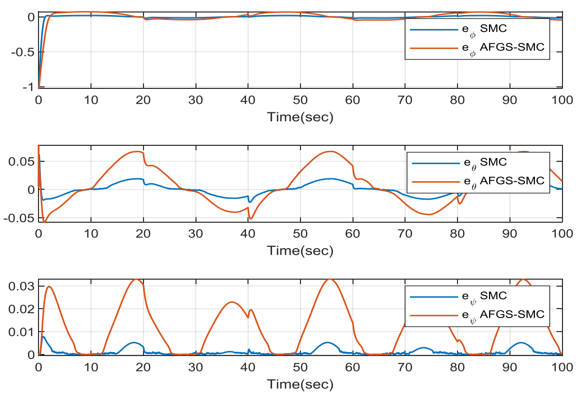

Figure 22. Attitude error under parameters uncertainty

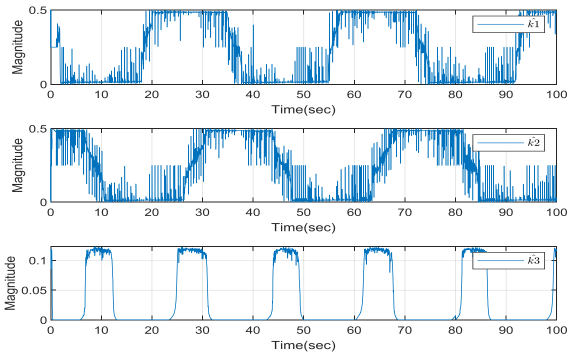

Figure 23. Control gains for AFGS-SMC parameters uncertainty

6. Conclusion

The dynamic and kinematics equation of the quadrotor unmanned aerial vehicles (UAV) has been briefly introduced. The classical sliding mode controller is designed as the inner loop controller for the quadrotor UAV. However, to reduce the chattering associated with the conventional SMC meanwhile overcomes the uncertainty in the quadrotor's mass, the adaptive fuzzy gain scheduling SMC techniques (AFGS-SMC) is implemented which provided a significant improvement in term of chattering reduction under two scenarios, the nominal parameters, and uncertainty in the mass of the quadrotor. However, it has been observed that the performance of the SMC without fuzzy is slightly better than the proposed AFGS-SMC in term of the trajectory tracking.

PD controller has been implemented as an outer loop controller to control the quadrotor position and generates the desired attitude and supply it to the inner loop AFGS-SMC. Finally, the performance of the proposed AFGS-SMC controller has been evaluated by simulation Matlab/Simulink, and compared with the classical SMC, in terms of chattering attenuation and uncertainty in the mass of the quadrotor UAV.

References

[1] O. Araar, "Quadrotor Control for Trajectory Tracking in Presence of Wind Disturbances," 2014 UKACC Int. Conf. Control, no. July, pp. 25–30, 2014.

[2] N. Ben Ammar, S. Bouallègue, and J. Haggège, "Fuzzy Gains-Scheduling of an Integral Sliding Mode Controller for a Quadrotor Unmanned Aerial Vehicle," vol. 9, no. 3, pp. 132–141, 2018.

[3] A. Reizenstein, "Position and Trajectory Control of a Quadcopter Using PID and LQ Controllers," 2017.

[4] A. L. Salih, M. Moghavvemi, H. A. F. Mohamed, and K. S. Gaeid, "Flight PID controller design for a UAV quadrotor," Sci. Res. Essays, vol. 5, no. 23, pp. 3660–3667, 2010.

[5] D. Lee, H. J. Kim, and S. Sastry, "Feedback linearization vs. adaptive sliding mode control for a quadrotor helicopter," Int. J. Control. Autom. Syst., vol. 7, no. 3, pp. 419–428, 2009.

[6] P. Mukherjee and S. L. Waslander, "Direct adaptive feedback linearization for quadrotor control," AIAA Guid. Navig. Control Conf. 2012, no. August, pp. 1–10, 2012.

[7] Z. Zuo, "Adaptive trajectory tracking control design with command filtered compensation for a quadrotor," J. Vib. Control, vol. 19, no. 1, pp. 94–108, 2012.

[8] L. I. Sen, L. I. Baokui, and G. Qingbo, "Adaptive Sliding Mode Control for Quadrotor Helicopters," no. 2, pp. 71–76, 2014.

[9] K. Runcharoon and V. Srichatrapimuk, "Sliding Mode Control of Quadrotor," 2013 Int. Conf. Technol. Adv. Electr. Electron. Comput. Eng., no. 1, pp. 552–557, 2013.

[10] A. H. Mazinan, M. F. Kazemi, and H. Shirzad, "An efficient robust adaptive sliding mode control approach with its application to secure communications in the presence of uncertainties , external disturbance and unknown parameters," vol. 36, no. 2, pp. 164–174, 2014.

[11] J. Zhu and K. Khayati, "A new approach for adaptive sliding mode control : Integral / exponential gain law," vol. 38, no. 4, pp. 385–394, 2016.

[12] S. V. C. Lien, Applications of Sliding Mode Control in Science and Engineering, vol. 709. 2017.

[13] U. Suleiman, M. B. Mu, T. A. Zarma, A. T. Salawudeen, S. Thomas, and A. A. Galadima, "Methods of Chattering Reduction in Sliding Mode Control : A Case Study of Ball and Plate System."

[14] J.-L. Chang, "On Chattering-Free Dynamic Sliding Mode Controller Design," J. Control Sci. Eng., vol. 2012, pp. 1–7, 2012.

[15] J. Jiang and M. Razeghi, "Neural Network Based Chattering Free Sliding Mode Control," Quantum, no. x, 1995.

[16] J. Baek, M. Jin, and S. Han, "A New Adaptive Sliding-Mode Control Scheme for Application to Robot Manipulators," IEEE Trans. Ind. Electron., vol. 63, no. 6, pp. 3628–3637, 2016.

[17] M. Rafimanzelat and M. J. Yazdanpanah, "A Novel Approach for Chattering Minimization in Sliding Mode Control."

[18] L. A. Zadeh, I. Introduction, and U. S. Navy, "Fuzzy Sets * -," vol. 353, pp. 338–353, 1965.

[19] K. M. Passino and S. Yurkovich, Fuzzy control. 2010.

[20] Y. Yang and Y. Yan, "Attitude regulation for unmanned quadrotors using adaptive fuzzy gain-scheduling sliding mode control," Aerosp. Sci. Technol., vol. 54, pp. 208–217, 2016.

[21] M. A. M. Basri, A. R. Husain, and K. A. Danapalasingam, "Robust chattering free backstepping sliding mode control strategy for autonomous quadrotor helicopter," Int. J. Mech. Mechatronics Eng., vol. 14, no. 3, pp. 36–44, 2014.

[22] H. T. Nguyen and M. Sugeno, "Fuzzy systems : modeling and control," Kluwer Handb. Ser. fuzzy sets, no. FSHS 2, p. xxi, 519 p., 1998.

[23] H. Boudjedir, O. Bouhali, and N. Rizoug, "Adaptive neural network control based on neural observer for quadrotor unmanned aerial vehicle," Adv. Robot., vol. 28, no. 17, pp. 1151–1164, 2014.

[24] Z. Li and X. Ma, "Model-free control of a quadrotor using adaptive proportional derivative-sliding mode control and robust integral of the signum of the error," no. October, pp. 1–15, 2018.

[25] S. Bouabdallah, "Design and Control of Quadrotors With Application To Autonomous Flying," École Polytech. Fédérale Lausanne, À La Fac. Des Sci. Tech. L'Ingénieur, vol. 3727, no. 3727, p. 61, 2007.

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